NASA Exploration Team (NEXT)

Human Exploration

Requirements for Future Nuclear Systems

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HUMAN EXPLORATION REQUIREMENTS

FOR FUTURE NUCLEAR SYSTEMS

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1.0 INTRODUCTION

1.1 *Purpose*:

This document shall serve to consolidate and to communicate current needs and requirements for nuclear systems and technologies in support of advanced human exploration missions.

1.2 *Background*:

The requirements within represent a current best understanding, and are subject to future change. Many of the requirements are also scenario dependent, especially with respect to specific mission implementation approach. In these cases, a mean value is at times presented as representative, with likely ranges appearing in the rationale.

Requirements are drawn from various sources, particularly advanced mission studies over the last 15 years. In the interest of brevity, this document will not attempt to review the applicable body of knowledge in any great depth. Supporting data and mission descriptions may be reviewed in a companion Design Reference Mission summary document, as well as other cited references.

Nuclear needs and requirements for robotic exploratory missions are explicitly considered out-of-scope for this document, as this issue is being actively and extensively pursued elsewhere within the agency. It is expected, though, that the high degree of similarity in design challenges will allow for significant overlap in potential technology and design solutions. Common technology approaches, where practical, should allow beneficial program efficiencies and progressive technology validation. For reference purposes, preliminary planning in the Nuclear Systems Initiative indicates power levels of 100-300 kWe may be required for robotic deep space exploratory missions to Jupiter, Neptune, and Pluto (12). Such systems would be comparable in scale to projected surface power needs for human missions, and though smaller than human propulsion needs, would exhibit similar functionality and desire for performance.

1.3 *Definitions*:

NEP Specific Mass ("Alpha"): Specific Mass, or "alpha", is defined as the ratio of NEP-specific hardware mass (including nuclear power system and electric propulsion system, but excluding propellant, tankage, payload, vehicle bus & structure) to conditioned electrical power (leaving the power module and entering the electric propulsion module). Units are expressed as "kg/kWe".

NEP Modularity: In specifying certain key NEP parameters such as power, it is important to distinguish between the rating of the system as a whole, and the rating of constituent elements or components. For example, a 6 MWe NEP system may actually be composed of two independent 3 MWe nuclear power systems, each with three 1 MWe power conversion loops, and feeding a total of six 1 MWe thrusters. The ultimate degree of desired modularization will reflect an optimal balance of reliability, economy of scale, mass, development issues, and commonality.

Surface Power Modularity: In specifying certain key surface power parameters such as power, it is important to distinguish between the rating of the system as a whole, and the rating of constituent elements or components. For example, a 60 kWe surface power "need" may be met through a single 60 kWe or larger power system, or two smaller 30 kWe systems, or some other combination, possibly with total power output greater than 60 kWe to allow for reliability or future growth. The ultimate degree of desired modularization will reflect some optimal balance of reliability, economy of scale, mass, deployment, development issues, and commonality.

1.4 _Acronyms_:

C&DH	Command and Data Handling
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
HEDS	Human Exploration and Development of Space
ISS	International Space Station
LEO	Low Earth Orbit
LOx	Liquid Oxygen
MMOD	Micro-Meteoroid and Orbital Debris
MWe	Megawatts-electric
NEP	Nuclear Electric Propulsion
PMAD	Power Management And Distribution
PV	Photovoltaic
RFC	Regenerative Fuel Cell
SEP	Solar Electric Propulsion

1.5 References:

1. "*Space Transfer Concepts and Analysis for Exploration Missions*", Gordon Woodcock et.al., Boeing Defense & Space Group, Report No. D615-10030-2, NASA Contract NAS8-37857, March 1991.
2. "*Integrated Mars Mission Analysis*", James Compton et.al., McDonnell Douglas Space Systems Company, IRAD Study, January 1992.
3. "*Fast Piloted Missions to Mars Using Nuclear Electric Propulsion*", Jeff George et.al., NASA Lewis Research Center, 9th Symposium on Space Nuclear Power Systems, Albuquerque, NM, January, 1992.
4. "*Piloted Mars Mission Planning: NEP Technology and Power Levels*", Jeff George et.al., NASA Lewis Research Center, 10th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, January, 1993.
5. "*Nuclear Electric Propulsion: A "Better, Safer, Cheaper" Transportation System for Human Exploration of Mars*", John Clark et.al., NASA Lewis Research Center, 11th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, January, 1994.
6. *NEXT Design Reference Missions 2002 Summary* (under dev.).
7. "*Principles Relevant to the Use of Nuclear Power Sources In Outer Space*"; United Nations Office for Outer Space Affairs.
8. "*First Lunar Outpost Study*", NASA internal study, 1992.
9. "*Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*", Stephen J. Hoffman and David I. Kaplan, NASA SP 6107, July 1997.
10. "*Reference Mission Version 3.0 Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*", Bret Drake, EX13-98-036, June 1998.
11. "*Reference Mission Version 4.0*", internal NASA study, December 1999.
12. "*Jupiter Moon Tour, Neptune/Triton Orbiter, Pluto Orbiter High Level Mission Trade Results*", internal study, Erik Nilsen, JPL, 5/22/02.

2.0 HEDS FUTURE NUCLEAR SYSTEMS

2.1 *Benefits and Limitations of Space Nuclear Solutions*:

Space nuclear approaches can be highly advantageous for solving key challenges to advanced human missions. Nuclear power systems offer large amounts of energy in relatively compact packages. The energy source is independent of insolation, making it attractive for missions traveling far from the sun, or to destinations with extended durations of darkness or nighttime, such as the moon. Nuclear propulsion systems can provide efficient space transport featuring fast transits with reduced propellant and overall mission mass requirements. Further, enabling mission performance can be provided in areas such as extended opposition stay times, broadened departure windows, and innovative abort modes. Abundant power can also translate into mass savings in other subsystems such as life support or in-situ consumables production, can enable new science investigations such as deep drilling or remote sensing, and can aid the general robustness and safety of human mission architectures.

At the same time, nuclear solutions are not a panacea for every engineering problem, nor are they appropriate choices for every mission. Nuclear programs may be expensive and will certainly require considerable development activity to implement. The constituent technologies themselves are inherently demanding, especially with respect to materials operating temperatures and radiation damage. Nuclear safety will be of paramount priority, and may increase the complexity of design and operations throughout the life cycle. The inherent radiation environment must be mitigated through time, distance, and shielding mass. Provisions must be made for secure disposal at end of life. Finally, testing and associated facilities may prove both expensive and challenging.

Alternative technologies to nuclear power and propulsion exist, some with extensive flight experience, and undergoing continuous development. Solar power, batteries, and fuel cells have powered the bulk of spaceflight systems to date. The gross solar array output of the International Space Station is planned to eventually exceed 200 kWe. Solar electric propulsion (SEP) has also attained a maturity for commercial station keeping, and is now accepted for primary propulsion of low powered science missions. These technologies, especially given continued development and evolution, may prove wholly satisfactory for near-earth in-space missions of moderate power level and difficulty, and for brief sorties to planetary surfaces.

More demanding future missions though, such as human survival through the 14 day lunar night, or rapid voyages to Mars and back, will require energies and mass efficiencies difficult to achieve through non-nuclear means. The definition of potentially enabling solutions to these missions, based on nuclear technologies, is the focus of this document.

2.2 *Scope of Considered Systems and Applications*:

This document specifies requirements for nuclear systems that are currently of most interest for implementing the "first wave" of advanced human exploration missions beyond low Earth orbit. Over the years, a wide array of nuclear solutions have been proposed, exhibiting a range of feasibility, technical maturity, and desirability for any given mission application. The systems specified in this document are of most immediate interest to fulfilling advanced human exploration missions, and have passed each of two selection criteria.

2.3 *First Selection Criterion – Enabling Performance:*

The first selection criteria considers the enabling or highly enhancing performance potential of a particular nuclear solution (i.e. a specific technology applied to a specific mission application). Given the technical and programmatic challenges to successful development, a given nuclear solution should offer enabling or greatly enhancing performance advantages over alternative non-nuclear solutions.

2.4 *Second Selection Criterion – Near-Term Feasibility and Maturity*:

The second selection criterion considers the demonstrated feasibility and maturity of a given nuclear solution. Concepts with relatively assured feasibility and demonstrated maturity are of most immediate interest for near-term applications. As examples, fission power and electric propulsion systems are established and well understood, at least for respective terrestrial and kilowatt-class applications. Challenges remain in scaling to higher temperatures or power levels, but the basic engineering principles are well understood. Conversely, technologies such as fusion or antimatter propulsion retain significant questions as to basic feasibility.

2.5 *Considered Mission/System Applications*:

Based on the previous two selection criteria, the following Mission/System applications are currently considered to be of most interest to advanced human exploration missions:

- Nuclear Electric Propulsion (NEP) Missions for Humans & Cargo beyond Earth Orbit

- Fixed Surface Nuclear Reactor Power Systems for Moon, Mars, and Asteroids.

2.6 *Required Overall Mission Probability of Crew Survival:* The overall mission probability of crew survival shall be 0.98, or better.

Rationale: Defined as the probability of a mission event, attributable to an element of the architecture, which would result in the loss of life or one or more crew members. The probability of crew survival should be no worse than the probability of crew survival of a current Shuttle mission summed with current International Space Station (ISS) missions over the same period of time as an assumed Mars mission. The estimate for a Space Shuttle mission catastrophic failure (loss of crew and vehicle) ranges from 1/100 to 1/500 per mission. The ISS probability of loss of crew is in the neighborhood of 1/333 for an 8 month mission, and is largely driven by the collision with micro meteoroid or orbital debris (MMOD). If this is an acceptable loss of crew probability for conducting current space science, then a Mars mission should be at least as acceptable for an equivalent mission, with the understanding that it is easier to return to Earth from low Earth orbit (LEO) than a heliocentric orbit.

2.7 *Required Overall Mission Probability of Success*: The probability of overall mission success shall be 0.95, or better.

Rationale: Defined as the probability of an event, attributable to an element of the architecture, which would result in loss of the defined mission objectives. The probability of mission success should be no worse than the probability of mission success of a combination Space Shuttle and ISS mission over an equivalent Mars mission. The probability of mission success includes the summation of loss of crew or vehicle, and the early return without achieving mission goals. Current estimates for crew return without completing the mission for Space Shuttle is about 1/50, based on two missions that resulted in an early return due to equipment malfunction. The estimates on evacuation over an 8 month mission for the ISS is about 1/20 for equipment malfunction, collision from MMOD or other vehicles, Shuttle unavailability, and crew illness. As stated before, the loss of crew and station is driven largely by MMOD.

3.0 BACKGROUND ON HUMAN NEP APPLICATIONS

3.1 *Function*: The NEP system transports crew and/or cargo in support of human exploration missions. The NEP system also provides primary onboard power for habitat and vehicle subsystems. The NEP system may also provide primary attitude control during thrusting periods.

3.2 *General Goals and Objectives*:

- Enable *fast transits* to reduce crew exposure to harm.
- Allow demanding missions to be performed for *reduced launch mass*.
- Entail multi-mission savings through *reuse* and *low resupply mass*.
- Exhibit robust operation and *high reliability* over the design lifetime.
- Provide *enhanced abort* options for a variety of scenarios over broad segments of the mission.
- Enhance *mission flexibility* thru widened departure windows.
- Provide a *power rich* environment for crew subsystems.
- Perform primary vehicle *attitude control* during thrusting periods.
- Where practical, *common* nuclear power and electric propulsion *technologies* should be used across human and robotic system applications.
- Where practical, *common* subsystems and *components* should be used across human and robotic systems.
- While meeting requirements for performance and safety, the system should be based on technologies of *sufficient maturity* to ensure successful and cost-effective development.
- The system should *facilitate* ground *testing*, and minimize need for new or complex facilities.
- The system should *facilitate* integration, packaging, storage, and approval for *launch*.
- The system should feature *minimal deployment* needs, and be easily integrated on orbit.
- The system should *facilitate* stable *operation*, and autonomous, crew, or ground control.

3.3 *Functional Allocation of NEP System Elements*: The NEP system shall be comprised of the following elements and subsystems:

- *Nuclear Power System* – provides conditioned electrical power. Includes reactor, shield, control, power conversion, heat rejection, and power management and distribution subsystems.
- *Electric Propulsion System* – converts electrical power into kinetic jet power and thrust. Includes electric thruster, power processing, thrust vector control, thermal, and propellant feed subsystems.
- *Tankage* – stores and thermally controls propellant.
- *Propellant* – serves as reaction mass for vehicle propulsion, and may vary with specific thuster type and specific impulse range.

- *Bus Module* – contains all remaining vehicle support and infrastructure subsystems such as structure, mechanisms, command and data handling (C&DH), attitude control, etc.
- *Payload Modules* – the mission specific payload, such as crew habitats, science instruments, landers, etc.

3.4 *Mars Mission Survey*:

A human mission to Mars shall be used as a benchmark mission for deriving requirements for NEP systems and technology. This mission embodies great scientific and public interest, and would likely be impractical to implement without some means of advanced propulsion.

The following table presents example NEP Mars mission and system concepts from a range of literature sources (References 1, 2, 3, 4, 5, 6). A variety of mission architecture approaches are represented, including opposition vs. conjunction class missions, “Split” (separate crew and cargo vehicles) vs. “All Up” (single vehicle for both crew and cargo), artificial gravity, mission opportunity, and staging orbits. The NEP vehicle systems vary in terms of reusability, provision for artificial gravity, power level, and technology level (reflected in specific mass). Care should be taken in directly comparing cases, as specific mission assumptions are likely to vary. Nonetheless, taken as a whole, this survey can be used as a reference for deriving high-level requirements. Additional cases, along with supporting detail, can be found in the references.

Table 1. Survey of Human Mars Missions Utilizing NEP.

REFERENCE	Electrical Power (MWe)	Full Power Life (yr)	Number Missions	Specific Mass (kg/kWe)	Mission Class	Artificial Gravity?	Stay Time (days)	Total Mission Duration (days)	Initial Mass (metric tons)
DRM 2002	6	4	3	6.7	Opposition	Yes	90	590	194
DRM 2002	8	4	3	5	Opposition	Yes	90	550	167
Clark, 1994	8	5	2	11.1	Conjunction	No	550	960	283
George, 1992	10	2	1	7.3	Opposition	No	30	418	265
George, 1992	15	2	1	4.7	Opposition	No	30	367	285
George, 1993	10	2	1	7.3	Conjunction	No	626	899	286
McD/Doug, 92	10	-	-	10	Conjunction	Yes	489	887	576
Boeing, 1991	40	-	-	4	Conjunction	Yes	600	1090	561

4.0 MISSION REQUIREMENTS FOR HUMAN NEP VEHICLES

4.1 *6-20 MWe Total Electrical Power*: The nuclear power system shall provide a floor threshold of 6 MWe of conditioned electrical power to the electric propulsion system, with an objective power of up to 20 MWe. The system shall further provide 50 kWe of housekeeping power for miscellaneous vehicle and payload needs.

Rationale: Power requirement varies with the specifics of a given mission architecture. Past studies have required power levels ranging from 6 MWe to 20 MWe or higher (see Section 3.8). 6 MWe represents a likely floor or threshold for less demanding architectures (Ref. 6, 4). Power levels for more demanding scenarios may be as high as 20 MWe (Ref. 1,4). It should be noted that there will be an "optimal" power level for performing a particular mission scenario, with higher power levels being often counter productive. The opposition and conjunction missions assessed in George 1992 and 1993 (Ref. 3,4) showed greatly diminishing returns after power levels of ~15-20 MWe. Higher power levels were able to only minimally reduce trip time, while greatly increasing initial mass as well as technical difficulty of the NEP system. Note also that total rated power may be achieved through modular assemblies of lower-power reactors and power conversion loops, i.e. it may be desirable to configure a 6 MWe system from two 3 MWe power generation plants, and to utilize that power through six 1 MWe electric thrusters. Habitat and vehicle housekeeping power are assumed to be "noise level" and are ignored for present purposes. A cargo vehicle variant, as used in "split" mission scenarios, would lie in the low end of the above power range, and is typically enveloped by the higher human vehicle requirement.

4.2 *4 year Effective Full Power Life*: The nuclear power system shall provide full rated power over an effective duration of 4 years.

Rationale: Effective Full Power Life is designed as the rated amount of time the system could continuously operate at full power. The actual operational life of the system will be greater than this value due to periods of quiescence between missions, stand-by modes during coasts and at Mars, and periods of partial power operation. Assuming a reusable system and departure from the earth-moon L1 Lagrange point, a 4 year full power lifetime allows the completion of three round trip Mars missions of 15 months thrusting time, with an additional 3 months remaining for disposal operations. This requirement applies to the nuclear power generation element in particular. Electric thrusters are excluded.

4.3 *4000-7000 sec Specific Impulse*: The electric propulsion system shall perform at an effective specific impulse of 4000 sec as a threshold, with objective value of up to 7000 sec.

Rationale: Optimal mission specific impulses for fast human Mars missions are typically in the 4000-7000 sec range. Like power level, there exists an "optimal" specific impulse for performing a given mission with balanced power level, flight time, and initial mass. Higher specific impulse, though more efficient at utilizing propellant, can require higher power levels to offset reduced thrust and maintain flight time.

4.4 *50% Efficient Electric Propulsion*: The electric propulsion system, including all power processing and thrusters, shall convert 50% or better of input electrical power into net useful thrust.

Rationale: Thruster efficiency is a key performance metric, determining the fraction of electrical power that can be harnessed as kinetic power and thrust. This value also determines how large and massive the required power plant must be to achieve a given thrust level. Higher values of thruster efficiency are always desirable, but will be constrained due to thruster technology, specific impulse, and lifetime issues. Efficiency values below 50% begin to rapidly increase electrical power requirement, vehicle dry mass, and degrade trip time.

4.5 *4-7 kg/kWe Specific Mass*: The total NEP system specific mass shall meet a desired objective value of 4 kg/kWe or less, while not exceeding a threshold value of 7 kg/kWe.

Rationale: NEP system specific mass is defined in Section 3.4. Though smaller values of specific mass are always beneficial from a mission performance perspective, there exists an inverse relationship with technology level and associated program cost and risk. The "best" specific mass will be the one just low enough to meet mission objectives. Past studies of human Mars missions (see Section 3.8) have required 4-7 kg/kWe specific mass to enable missions of desirably low mass and mission duration.

4.6 *Restartable*: The system shall be capable of being started or restarted under cold or hot standby conditions.

Rationale: The vehicle will encounter coast periods and down time between missions.

4.7 *Throttleable*: The system shall be capable of throttling between full rated power, a lower power housekeeping mode, and a zero power hot standby mode.

Rationale: Power levels other than full are desirable during different mission phases.

4.8 *Microgravity*: The reactor and power conversion subsystems shall operate nominally under microgravity conditions.

Rationale: The spacecraft design may not allow for the provision of artificial gravity. Note this requirement may be applied in parallel with, or in lieu of, Requirement 4.9.

4.9 *Artificial Gravity*: The reactor and power conversion subsystems shall operate nominally at full power under 1.0 g conditions, with the ability to provide housekeeping mode over the range of 0 through 1.0 g conditions.

Rationale: Artificial gravity may be required as a countermeasure to address human physiology concerns for long duration spaceflight. It is assumed herein that a provision for artificial gravity for the crew implies a rotating spacecraft (vs. crew centrifuge), and further that the rotating spacecraft would also provide a ~1 g environment to the reactor and power conversion. A key programmatic advantage to this approach would be the ability to perform “relevant environment” testing and certification on Earth. Additional engineering advantages may possibly be leveraged through buoyancy-aided coolant transport. Note this requirement may be applied in parallel with, or in lieu of, Requirement 4.8.

4.10 *(Reserved)*:

4.11 *NEP System Reliability:* The human NEP vehicle shall achieve 100 % of required performance specifications (i.e. power, thrust, specific impulse, etc.) with a reliability of 0.995 per mission. The human NEP vehicle shall be able to return crew to Earth orbit in a nominal or contingency mode (i.e. under reduced power, etc.) with a reliability of 0.998.

Rationale: These values represent allocations of 10% of the overall mission risks specified in Requirements 2.6 and 2.7.

4.12 *Probability of Fission Product Release to the Earth Environment:* The probability of release of fission products to the earth environment, including launch criticality accidents and inadvertent reentry, shall be 1/100,000 or lower.

Rationale: Current nuclear power plants carry probabilities of core meltdown and early release of 1/100,000 or lower.

4.13 *Low reactor dose to crew:* The NEP system shall not contribute more than 5 rem/yr to the crew’s total mission radiation dose.

Rationale: As mission dose due to natural sources is expected to be on the order of 10's of rem, the specified dose will add only marginally to the crew's total mission dose. Additionally, NEP-enabled reductions in transit times and exposure may actually reduce total mission dose (natural + reactor) due to reduced transit times and exposure.

4.14 *Fissile Material*: Nuclear reactors shall use only uranium-235 as fuel.

Rationale: "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7). Furthermore, uranium-based fuels are most readily available, have the highest experience base, and avoid toxicity issues associated with other fissile materials such as plutonium-239. Note, deleted original reference to "highly enriched" U-235.

4.15 *Initial Criticality*: Nuclear reactors shall not be made critical before they have reached their operating orbit or interplanetary trajectory.

Rationale: "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7). This requirement does not apply to zero power or other testing prior to launch.

4.16 *Inadvertent Criticality*: The design and construction of the nuclear reactor shall ensure that it cannot become critical before reaching the operating orbit during the following events: rocket explosion, re-entry, impact on ground or water, submersion in water or water intruding into the core.

Rationale: "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7).

4.17 *Disposal*: Disposal shall ensure the risk of release of fission products into the earth's environment to be no more than 2 / 1,000,000 in 300 years.

Rationale: "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7). The specification is computed through allocation of 20% of the risk allowed in the preceding requirement on "Probability of Fission Product Release to the Earth Environment".

4.18 *(Reserved)*:

4.19 *(Reserved)*:

4.20 *(Reserved)*:

4.21 *Contamination*: The system shall minimize external contamination of itself and vicinity by effluents such as fission products, coolants, working fluids, and hazardous propellants.

Rationale: Enhanced crew safety and vehicle reliability. Minimized impact to crew operations in the vicinity. Further analysis is required to develop tolerances for specific materials and failure mechanisms. Planetary protection requirements may also apply.

5.0 HUMAN NUCLEAR SURFACE POWER APPLICATIONS

5.1 Function: The nuclear surface power system provides primary power generation and distribution for human exploration missions to the surface of the Moon, Mars, and asteroids.

5.2 General Goals and Objectives:

- Provide a *power rich* environment for human surface missions.
- Exhibit robust operation and *high reliability* over the design lifetime.
- Allow for a *low incremental* increase in crew *radiation dose* through time, distance, and shielding.
- Exhibit simple, stable *operation* capable of autonomous *control*.
- Design for ease of *deployment* with minimal required assembly or construction.
- Be compatible with the varied thermal and chemical *environments* of the Moon, Mars, and expected asteroid environment
- Exhibit modest *mass*.
- Exhibit modest packaged *volume*.
- Where practical, *common* nuclear power *technologies* should be used across human and robotic system applications.
- Where practical, *common* subsystems and *components* should be used across human and robotic systems.
- While meeting requirements for performance and safety, the system should be based on technologies of *sufficient maturity* to ensure successful and cost-effective development.
- The system should *facilitate* ground *testing*, and minimize need for new or complex facilities.
- The system should *facilitate* integration, packaging, storage, and approval for *launch*.

5.3 Functional Allocation of Surface Power System Elements: The nuclear surface power system shall be comprised of one or more of each of the following elements:

- *Nuclear Power Element* – provides unconditioned electrical power. Includes reactor, shield, control, power conversion, and heat rejection subsystems.
- *Primary PMAD Element* – provides control, regulation, and distribution of electrical power to (possibly remote) users.
- *Deployment Element* – provides all necessary deployment services between landing and initial startup. May include surface transport to a remote location, radiator deployment and other assembly, transport and connection of power distribution cables, and construction or excavation of in-situ radiation shielding.

5.4 *Surface Power Mission Survey*:

The following Table presents power requirements from recent studies of human missions to the surface of the Moon and Mars (References 8, 9, 10, 11). Average powers are presented both for day and night, as well as the assumed power generation concept (nuclear or solar). Though it is beyond the scope of this document to delve into system concepts and technologies, it should be noted that the choice of "solar vs. nuclear" approaches does impact the surface mission operational approach, and thus the respective power need. Solar systems generate power during day periods, thus it is advantageous to shift all possible loads to the day, while minimizing needs for power and energy storage at night. Nuclear systems are largely insensitive to the day/night cycle, and it is advantageous to achieve a "balanced" load to reduce overall system rating.

Table 2. Survey of Power Needs for Human Surface Missions.

REFERENCE	Destination	Day Average Power (kWe)	Night Average Power (kWe)	Technology
First Lunar Outpost (Ref. 8)	**Moon**	**13**	**9**	**PV/RFC**
DRM 1.0; ISRU only (Ref. 9)	**Mars**	**60**	**60**	**Nuclear**
DRM 1.0; Habitat only (Ref. 9)	**Mars**	**25**	**25**	**Nuclear**
DRM 3.0 ; ISRU only (Ref. 10)	**Mars**	**45**	**45**	**Nuclear**
DRM 4.0; Habitat, Rovers (Ref. 11)	**Mars**	**37**	**9**	**PV/Battery/RFC**

6.0 MISSION REQUIREMENTS FOR NUCLEAR SURFACE POWER

6.1 *Electrical PowerOutput*: The nuclear power system shall provide to the user the following electrical power output, dependent on surface mission architecture:

A: Habitat and science	*30 kWe*
B: In-Situ Propellant Production	*60 kWe*
C: Habitat + Propellant Production	*90 kWe*

Rationale: Power requirement varies with mission architecture approach. The above values are representative of three different Mars scenarios. A mission with no propellant production will require ~30 kWe to power the habitat, recharge rovers, and perform other small experiments (Ref. 9). A mission that produces LOx/Methane ascent propellants prior to crew arrival will require ~60 kWe during production mode, ramping down to 30 kWe once crew arrives (Ref. 9, 10). A mission requiring propellant production (possibly for a future mission) in parallel with human occupation will require 90 kWe (Ref. 9, 10). Note all values are to be provided to the user, at the user's location. Any losses such as distribution from a remote locale should be accommodated internally to the power system.

These requirements could be met with various configurations of number and unit size power modules. Scenario A could be met with a single 30 kWe module, possibly with 1 or 2 additional modules for redundancy. Scenario B could be met with one or more 60 kWe modules, or two or more 30 kWe modules. Scenario C could be with one or more 90 kWe modules, two or more 60's, or three or more 30's. Each scenario will provide different levels of total mass, reliability, and ease of deployment.

6.2 *15 year Effective Full Power Life*: The nuclear power system shall provide full rated power over an effective duration of 15 years.

Rationale: A key benefit of nuclear power lies in its very high energy density. However, development, production, launch, transport, and deployment of such systems will be non-trivial. Lifetimes in the 10 to 20 year range are readily achievable (at least from an energy density standpoint), and would be preferable to more frequent deployment of shorter-lived systems. A requirement of 15 years is levied as intermediate. This value is subject to future modification based on sensitivity studies of overall system mass vs. life, and particularly ramifications of fuel and material degradation and creep at temperature and exposed to planetary environments.

6.3 *(Reserved)*:

6.4 *(Reserved)*:

6.5 *2000 kg Unit Module Mass*: Each independent nuclear power module (consisting of reactor, shield, power conversion, heat rejection, power management and distribution, structure, and surface transport) shall have a mass of no more than 2000 kg.

Rationale: Power modules must be launched, transported, and landed at the desired destination. The module may then need to be further transported from a landing site to a remote operations and/or disposal site. Increasing mass is detrimental to both activities. A maximum limit of 2000 kg is levied based on likely rover tow limits, and the landed payload capacity of an EELV Heavy. Lower masses are highly desirable, and would benefit overall mission launch requirements, surface transport, the ability to direct deploy a power module on an ELV, and the potential to ELV direct deploy a power module with significant science (such as a drill).

6.6 *Restartable*: The system shall be capable of being started or restarted under cold or hot standby conditions.

Rationale: The system will encounter coast periods and down time between missions.

6.7 *Throttleable*: The system shall be capable of throttling between full rated power, and a zero power hot standby mode.

Rationale: Power levels other than full are desirable at different mission phases.

6.8 *(Reserved)*:

6.9 *(Reserved)*:

6.10 *(Reserved)*:

6.11 *Power System Reliability:* In order to assure mission success, the power system shall achieve 100 % of required performance specifications (i.e. power, etc.) with a reliability of 0.995 per mission.

Rationale: This value represents an allocation of 10% of the overall mission risks specified in Requirement 2.7. The requirement may be achievable through a single power generating module with large internal redundancy, a series of parallel modules, or combination of the two approaches.

6.12 *Probability of Fission Product Release to the Earth Environment:* The probability of release of fission products to the earth environment, including launch criticality accidents and inadvertent reentry, shall be 1/100,000 or lower.

Rationale: Current nuclear power plants carry probabilities of core meltdown and early release of 1/100,000 or lower.

6.13 *Low reactor dose to crew:* The power system shall contribute no more than 5 rem per year to the crew's total mission radiation dose.

Rationale: As mission dose due to natural sources is expected to be on the order of 10's of rem, the specified dose will add only marginally to the crew's total mission dose.

6.14 *Fissile Material*: Nuclear reactors shall use only uranium-235 as fuel.

Rationale: "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7). Furthermore, uranium-based fuels are most readily available, have the highest experience base, and avoid toxicity issues associated with other fissile materials such as plutonium-239. Note, deleted original reference to "highly enriched" U-235.

6.15 *Initial Criticality*: Surface reactors shall not be made critical prior to emplacement in their permanent operating location.

Rationale: Adapted from "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7). This requirement does not apply to zero power or other testing prior to launch.

6.16 *Inadvertent Criticality*: The design and construction of the nuclear reactor shall ensure that it cannot become critical before reaching the operating station during the following events: rocket explosion, re-entry, impact on ground or water, submersion in water or water intruding into the core.

Rationale: "Principles Relevant to the Use of Nuclear Power Sources In Outer Space"; United Nations Office for Outer Space Affairs (Ref. 7).

6.17 *Disposal*: At end-of-life, a fixed (non-mobile) surface power plant shall be disposed of in-place. The system shall be capable of an assured means of permanent shut-down.

Rationale: Relocation of a radioactive power system at end-of-life may be difficult to accomplish, or to assure to a high degree of reliability. Initial and permanent location in an area remote to the main point of human operations (and habitat), possibly using terrain as shielding, would serve to mitigate crew dose and facilitate in-place disposal. The selected power plant site should be geologically stable, and have low volatile ice (water or CO2) inventory on the surface or near subsurface. The operating/disposal site shall be selected so as to accommodate indefinite storage.

6.18 *Lunar Environment*: The system shall be capable of nominal operations in the lunar surface environment.

Rationale: The Moon is a likely application. This requirement entails consideration of 0.18 gravity; chemical compatibility with lunar regolith and dust; near-vacuum pressure; thermal; electromagnetic; and other considerations. This requirement may in future be applied in lieu of or in conjunction with requirements for Mars and Asteroid/Phobos/Deimos compatibility.

6.19 *Mars Environment*: The system shall be capable of nominal operations in the Mars surface environment.

Rationale: Mars is a likely application. This requirement entails consideration of 0.38 gravity; chemical compatibility with atmosphere, dust, and surface materials; thermal; pressure; electromagnetic compatibility; and other considerations. This requirement may in future be applied in lieu of or in conjunction with requirements for Lunar and Asteroid/Phobos/Deimos compatibility.

6.20 *Asteroid, Phobos, Deimos Environment*: The system shall be capable of nominal operations on asteroids, Phobos, or Deimos.

Rationale: These are possible applications. This requirement entails consideration of microgravity; chemical compatibility with dust and regolith; near-vacuum; thermal; electromagnetic; environmental radiation; and other coniderations. This requirement may in future be applied in lieu of or in conjunction with requirements for Lunar and Mars compatibility.

6.21 *Contamination*: The system shall minimize external contamination of itself and vicinity by effluents such as fission products, coolants, and working fluids.

Rationale: Enhanced crew safety and system reliability. Minimized impact to crew operations in the vicinity. Further analysis is required to develop tolerances for specific materials and failure mechanisms. Planetary protection requirements may also apply.